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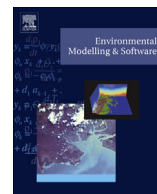
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Multi-factor, multi-state, multi-model scenarios: Exploring food and climate futures for Southeast Asia



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ABSTRACT

Decision-makers aiming to improve food security, livelihoods and resilience are faced with an uncertain future. To develop robust policies they need tools to explore the potential effects of uncertain climatic, socioeconomic, and environmental changes. Methods have been developed to use scenarios to present alternative futures to inform policy. Nevertheless, many of these can limit the possibility space with which decision-makers engage. This paper will present a participatory scenario process that maintains a large possibility space through the use of multiple factors and factor-states and a multi-model ensemble to create and quantify four regional scenarios for Southeast Asia. To do this we will explain 1) the process of multi-factor, multi-state building was done in a stakeholder workshop in Vietnam, 2) the scenario quantification and model results from GLOBIOM and IMPACT, two economic models, and 3) how the scenarios have already been applied to diverse policy processes in Cambodia, Laos, and Vietnam.

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Software and data availability

The following models were used in this study. The table below lists the institutions and co-author who should be contacted with respect to the specific model.

Models Cited.

Model	Supporting Institution	Author to contact for more information	Email
GLOBIOM	IIASA	Amanda Palazzo	palazzo@iiasa.ac.at
IMPACT 3	IFPRI	Daniel Mason-D'Croz	d.mason-dcroz@cgiar.org
OLDFAR		Steven Lord	steven.lord@adelaide.edu.au
LANDSHIFT	University of Kassel	Benjamin Stuch	stuch@cesr.de

GLOBIOM and IMPACT 3 are described in some detail in the paper. Full documentation for both models is available online.

- GLOBIOM (Havlik et al., 2014): www.pnas.org/content/suppl/2014/02/19/1308044111.DCSupplemental
- IMPACT 3 (Robinson et al., 2015): <http://ebrary.ifpri.org/cdm/ref/collection/p15738coll2/id/129825>

OLDFAR is available upon request in English and Spanish for Windows (32 and 64 bit), MacOS, and Linux.

A description of the LANDSHIFT model is provided in [Appendix A](#) of the Supplement.

1. Introduction

Policy-makers and planners in all sectors related to socioeconomic development, environmental change, and the water-food-energy nexus are faced with unprecedented challenges as they plan for a rapidly changing world (Erickson et al., 2009). The challenges of fundamental uncertainty and the impossibility of gaining full knowledge about system dynamics are compounded by human cognitive biases (Tversky and Kahneman, 1974) and the diversity of world views and interests that exists among system actors (Dryzek, 1997).

Forecasting a 'most likely' future and planning accordingly is often impossible and potentially dangerous in complex systems. Yet, decision-makers must respond to current pressures while also engaging with future uncertainty in a meaningful way to devise robust and flexible policies that will function in a variety of future contexts (Kok, 2007; Vermeulen et al., 2013). In response to these needs, new tools and methodologies have been developed, which incorporate an improved understanding of the decision-making process when faced with uncertainty. Such tools and methodologies can create a varied possibility space, where decision-makers can consider the potential effects of future stressors, such as climate change, socioeconomic development, environmental degradation, and political instability. The development and use of multiple scenarios is one approach to create this possibility space and apply it to planning (van der Sluijs, 2005; Vervoort et al., 2014; Herrero et al., 2014; Trutnevyte et al., 2016). Well-designed scenarios have the potential to combine many factors of change into comprehensible and integrated narratives (Xiang and Clarke, 2003; van der Heijden, 2005).

Many methods to develop and use scenarios to inform decision-making exist. The challenge is to ensure a highly diverse set of scenarios to supply decision-makers with a broad range of alternative futures in which to test policies (van der Heijden, 2005). This is challenging, as scenario development, even when involving diverse stakeholders, can be limited in scope. To create a broad possibility space, we must start with a broad range of perspectives, expertise, and opinions of how the future may unfold. To ensure this breadth is maintained, an extended group of stakeholders should be involved throughout the scenarios' development and use (Petersen et al., 2011). However, this diversity can threaten to overwhelm scenario development before it even starts. In order for the scenarios to be applicable in models and useful to decision-

makers, this diversity must be channeled into a manageable number of alternative futures.

Quantifying scenarios for use in models risks losing scenario richness, as models will need to streamline and summarize the scenario narrative (Siebenhüner and Barth, 2005). Funneling scenarios through a single model especially risks reducing the range of possibilities in the quantification of the scenarios through a single interpretation of future stressors (Volkery et al., 2008). Despite this, models are powerful tools that allow quantitative ex-ante scenario analysis, a feature valued by decision-makers. Therefore, to maintain scenario diversity while providing valuable quantification, scenarios should be simulated across a multi-model ensemble.

This paper presents a participatory scenario development process conducted for Cambodia, Viet Nam, and Laos, which focuses on the exploration of a large scenario possibility space. We discuss the challenges and tradeoffs associated with creating and maintaining this possibility space through a case study. This case study presents how four regional socioeconomic scenarios were created in an interactive and inclusive scenario development process. We then describe how multiple models were used to quantify these scenarios and link them to the IPCC community's Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs, Moss et al., 2010; O'Neill et al., 2014), while maintaining scenario diversity. Finally, we summarize the results of these quantified scenarios, and describe how they have guided policy and investment plans in Southeast Asia.

2. Case study: scenarios for policy development in Southeast Asia

November 2013, in Ha Long, Viet Nam, 30 stakeholders from government agencies, NGOs, academia, the private sector, and the media, from Cambodia, Laos, and Viet Nam explored key regional drivers of change as part of a regional scenario building process. This process, one of 7 regional efforts led by the CGIAR Research Program on Climate Change, Agriculture, and Food Security (CCAFS, Palazzo et al., 2014; Vervoort et al., 2014), was done in collaboration with the United Nations Environment Programme's World Conservation Monitoring Centre (UNEP WCMC). It had the objective of creating diverse, stakeholder-driven scenarios to test and develop regional policies and investment strategies on climate-resilient agriculture and food systems, while exploring potential environmental tradeoffs. Taking a regional approach allowed for the creation of a common framework that could be applied to different policy development processes at regional and national levels. The regional scale also served as an ideal bridge between the global and national perspective, and is often the most appropriate scale of analysis for transboundary environmental and development issues.

The decision to focus the regional work on Cambodia, Laos, and Viet Nam was made for several reasons. Limiting participation to stakeholders from a few countries ensured there was a wide range of stakeholders representing each country, allowing for a robust and multi-disciplinary discussion. These three countries share extensive land borders, and have coordinated across boundaries in the past as a part of ASEAN and the Mekong River Commission. These past experiences facilitated conversations surrounding the

creation of integrated regional scenarios. While key regional actors like Thailand and China were not present, the role they play in the region was discussed in the development of the scenarios.

The scenarios were quantified in two spatially explicit partial-equilibrium global agricultural economic models and one high resolution land-use, land cover model, and linked to global socio-economic and climate scenarios (SSPs/RCPs, O'Neill et al., 2014; O'Neill et al., 2015). This linking to global scenarios was done with a focus on coherence, ensuring the scenarios were compatible with the global context, but sufficiently independent to target regional policy concerns (Zurek and Henrichs, 2007). The scenario outputs then provided valuable plausible futures with quantified results, which policy-makers used to weigh the costs and benefits of different policies and investment plans. To date these scenarios have been used in the 3 participating countries to inform an investment proposal process in Vietnam, to improve Cambodia's agricultural climate adaptation plan, and to inform Laos's social development program.

3. Scenario development process and results

3.1. Definition of regional scenarios

The scenario development process started with pre-workshop interviews to prepare participants to consider factors of change and scenarios. The scenarios were then created following a five step process where participants 1) identified factors of change; 2) selected four primary factors of change based on uncertainty and relevance; 3) identified factor-states; 4) combined the factor-states into 4 diverse scenarios using the OLDFAR model; and 5) clarified the internal logic of the scenarios through scenario narratives and semi-quantification.

Step 1: identifying and clustering factors of change

To ensure inputs were drawn from all stakeholders and not only the most vocal, all participants were asked to pair up, and in five minutes list (on individual pieces of paper) factors of change affecting food security, rural livelihoods, and the environment. Participants repeated this exercise six times, each time with a different partner, ensuring a large number of factors were identified. All the factors were then collected and randomly redistributed to the participants. The participants were then asked to place all factors in a publicly visible space (e.g. stuck to a wall) and cluster similar factors. By the end of this step, the factors of change were aggregated transparently from nearly 150 to a more manageable 34.

Step 2: selecting and defining primary factors of change

Of these 34 factors, participants voted for their 3 most uncertain factors and their 3 most relevant factors as they pertain to food security, rural livelihoods, and the environment. This consensually narrowed the number of factors to four primary factors of change, while ensuring the factors maximized relevance and uncertainty for decision-makers (Chaudhury et al., 2013). The four primary factors identified were (1) *Agricultural Investment*, (2) *Enforcement capacity and regional collaboration*, (3) *Land degradation through land-use change*, and (4) *Markets*. Once the primary factors were established, a consensus understanding of what each factor would encompass had to be documented. This was done in a plenary discussion where participants defined the primary factors, ensuring the factors represented key regional issues, without being focused on specific policies (e.g. five year economic plan, deforestation legislation, etc.) to encourage greater flexibility of use in scenario

development. As a part of this process, the 30 remaining factors were clustered together as sub-factors under the most relevant primary factor ensuring all relevant issues were included in the scenario semi-quantification. Table 1 summarizes the results of the factor voting, and the coloring of the text reflects how the sub-factors of change were clustered within the four primary factors.

Step 3: Identifying factor-states

Participants were separated into four groups (one for each factor) to identify plausible, "extreme", and mutually exclusive future states (e.g. low vs. high growth), for their respective factor. Extreme states were necessary to ensure the scenarios are significantly different from each other, as well as the present. When necessary more than two extreme states were allowed, as was the case for *agricultural investment* and *markets*, where three extreme states were identified. Table 2 summarizes the extreme states for each of the four primary factors of change.

Step 4: Combining the factor-states and creating scenario skeletons

A selection of one factor-state from each factor of change from Table 2 produces a scenario skeleton, which can be represented by a numerical string. For example, a scenario with high private investment in agriculture, weak enforcement capacity and regional collaboration, high land degradation through land-use change, and unregulated markets would be represented by the string: (1, 2, 2, 2). Not all of the factor-states in Table 2 are compatible with each other. To turn these skeletons into full scenarios, participants developed a compatibility matrix to determine factor-state compatibility, a standard method to examine the plausibility of factor-states through pairwise comparisons (Zwicky, 1969; Rhyne, 1981, 1995; Coyle et al., 1994; Rhyne, 1995; Godet, 2006; Ritchey, 2006). In these pairwise comparisons, the participants ranked the factor-state combinations as: (0) not possible; (1) uncertain/disagreement; or (2) possible. For example, participants were asked "is *weak enforcement and regional collaboration* compatible with a *common and regulated regional market*: 0. Not possible, 1. Maybe possible, 2. Definitely possible". These three grades allow for identifying compatibility between factor-states, without grading likelihood, something we wanted to avoid to ensure the scenarios provided a wide range of plausible futures.

Once the compatibility matrix was created, 21 of 36 scenario skeletons were still plausible. There are 5985 possible ways to choose a subset of 4 scenarios from these 21 plausible scenarios; however, not all of these subsets are equally diverse. The number of combinations was too large to do the selection manually; thus, it was decided to use OLDFAR to select a subset of six diverse scenarios. OLDFAR is an ideal tool for this task as it goes beyond the pairwise checks of a compatibility matrix or simple difference metrics (i.e. Euclidean or Manhattan distance between scenario strings), by using a robust optimization that maximizes diversity through third- and fourth- order comparisons (Lord et al., 2015). This ensured a wide possibility space across all of the potential 6 scenarios. Participants were then asked to vote for 4 of these 6 scenario skeletons to develop into complete scenarios. This transparent and democratic selection process helped build legitimacy and ownership of the final scenario set, and the result of this final scenario selection is summarized in Table 3.

Step 5: Building regional scenario narratives

In this step, participants clarified the internal logic of the scenarios through defining the scenario narratives and semi-

Table 1
Results of factor ranking and clustering.

	Relevance									
	Votes	0	1	2	3	4	5	7	12	13
Uncertainty	0	Capacity, Environ. regulation, Overfishing, Waste Management, Industry	Ag. labor, Technology		Ag. changes, Pollution	Urbanization		Education	Land degradation	
	1	Knowledge, Floods		Econ. Growth			Deforestation			Improved Ag production
	2	Health, Mining, Inequality	Biodiversity				Strength of governance, Population		Ag. Land	
	3	Food Availability, Invest in Environment								
	4	Infrastructure, Migration	Disaster							
	5							Ag. Investment		
	7	Regional Cooperation								
	9	Water								
	10		Conflict							
	20							Markets		
	Primary Factors of Change: Agricultural Investment, Enforcement capacity and regional collaboration, Land degradation through Land-use change, Markets									

Note: Each workshop participant voted for their 3 most relevant and their 3 most uncertain factors. This table shows the results of the participants' votes on both dimensions. The four primary factors were chosen to maximize votes on both dimensions (lower right corner of the table). The boxes containing the four primary factors are highlighted with a darker border. The coloring illustrates how all of the other factors were clustered as sub-factors of change within each of the four primary factors of change

Table 2
Southeast Asia primary factor-states.

Agricultural investment	Enforcement capacity and regional collaboration	Land degradation through land-use change	Markets
1. High public and private investment 2. Unbalanced, high private investment only 3. Low public and private investment	1. Strong enforcement and regional collaboration 2. Weak enforcement and regional collaboration	1. Low degradation 2. High degradation	1. Common regulated market 2. Unregulated market 3. Protectionist and closed market

quantification. The scenario skeletons (see Table 3) provided the general framework for the narratives (Table 4), with additional content derived from considering the sub-factors of change listed in Table 1. Participants developed diverse and coherent narratives, while exploring the interactions and combined effects of factors of change, a strength of this method (Xiang and Clarke, 2003). Key to

this narrative building was to first imagine what a future world defined by the selected extreme factor-states would be like, and then backcast (look backwards from the future) a series of events that would tie together this future to the present. This process defined the dynamics of change of the scenario, and ensured participants imagined novel and diverse futures, with their own

Table 3
Southeast Asian scenario skeletons.

Scenario	Agricultural investment	Enforcement capacity and regional collaboration	Land degradation through land-use change	Markets
Land of the Golden Mekong	High public and private investment	Strong enforcement and regional collaboration	Low degradation	Common regulated market
Buffalo, Buffalo	Unbalanced, high private investment only	Weak enforcement and regional collaboration	High degradation	Unregulated market
The Doreki Dragon	Unbalanced, high private investment only	Strong enforcement and regional collaboration	High degradation	Common regulated market
Tigers on a Train	Low public and private investment	Strong enforcement and regional collaboration	Low degradation	Protectionist and closed market

Table 4
Scenario narrative summary.

<p>Land of the Golden Mekong</p> <p>Unification of Southeast Asia on political, economic and environmental issues gradually becomes a reality. Aging population and insufficient low-skill labor availability poses a challenge, leading to increasing migrant competition in the working class. This is a challenge for the region to manage increasing migration and urbanization. Ultimately, institutions, which are strong and inclusive, can manage the development process, leading to significant improvements in food security, livelihoods, and the environment. Climate resilience is therefore improved, although biophysical vulnerabilities remain, especially in the form of extreme events.</p> <p>Buffalo, Buffalo; water flows uphill</p> <p>Initially, ASEAN cooperation increases. However, by 2020 problems arise, with major corruption scandals weakening national governments. The private sector in response to energy and food prices starts to increasingly acquire land, putting pressure on small shareholder farmers. Food production declines, leading to more migration and societal conflict. By 2050, unsustainable agricultural intensification has led to concentration of agricultural land, and a focus on processed foods. There are issues of inequality and access to food. Poor environmental management leads to deforestation and conflicts within ASEAN. Though attempts continue to be made to improve conditions across sectors, general environmental and socioeconomic situation of the region declines.</p>	<p>The Doreki Dragon</p> <p>ASEAN facilitates the development of a regional market, which spurs the growth of big businesses across the region. The agriculture sector industrializes through the use of GMOs and other advanced technologies. However, through this process large producers dominate at the expense of small-shareholders, who become laborers on industrial farms, or are forced to the cities to find work. Rapid urbanization and industrialization leads to greater environmental degradation. This leads to a very unequal society, where food security is a major concern in the lower classes, and climate resilience is decreasing.</p> <p>Tigers on a Train</p> <p>Regional collaboration within Southeast Asia increases, but is coupled with increasing protectionism against outside economic influences. High food prices in the near future leads to targeted investments in agriculture, which spur the sector to industrialize with a focus on value added products. This focus on agriculture ebbs over time. Protectionist policies lead to tensions with China and by 2050, threatens to cripple the regional economy. Climate resilience and food security are threatened through increasing inequality, and a lack of investment in a sustainable agricultural development in the final decades of the scenario.</p>
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challenges and opportunities, before connecting them to the present (Kok et al., 2011).

To develop scenarios that could be used and reused by various groups of decision-makers, it was necessary to discuss with participants (1) the role of decision-maker agency to ensure the scenarios contained strategic (within the control of the scenario end-user) and contextual (outside the end user's sphere of influence) elements (van der Heijden, 2005; and Börjesson et al., 2006); and (2) the importance of avoiding purely utopian or dystopian scenarios.

A careful consideration of the role of control and context is critical. Completely strategic scenarios, focusing only on change within the control of decision-makers will fail to consider the effects of changes occurring outside their field of influence. At the other extreme, exclusively contextual scenarios may be too abstract, and advocate a purely adaptive approach to policy-making. Broadly, these regional scenarios skewed towards the strategic, as most of the factors of change were within the scope of control of some of the scenarios' intended users. However, this was balanced by including a few purely contextual elements such as climate change and global markets, which were simulated by the global models in which the scenarios were quantified. Additionally, as the intended scenario users are at the national and sector levels (i.e. government ministries, donor groups, private sector groups, etc.), with limited control of issues outside their domain, this meant that the same scenario element that might be strategic for one group of scenario users could be considered contextual for other users.

Once completed, different scenarios can be considered more or less desirable. It is important, however, to avoid imagining 'perfect'

or 'perfectly imperfect' futures to ensure the scenarios would be plausible and useful. Utopian futures fail to consider the downsides and unintended consequences of generally positive changes, such as the policy challenges of increasing expectations raised by societal improvements. Dystopian futures, on the other hand, fail to consider human agency, and the many ways in which people attempt to overcome challenges and identify new opportunities that may emerge. To avoid utopian/dystopian scenarios, participants were asked to consider the unique challenges and opportunities each future scenario would present policy-makers. For example, in 'The Land of the Golden Mekong', a generally optimistic scenario, potential challenges with demographic change and migration were explored, whereas in 'Buffalo, Buffalo', a more pessimistic scenario, included narrative elements describing attempts to mitigate the negative trends in the overall scenario (Table 4).

Once the scenario narratives were established, participants provided semi-quantitative information for each of the sub-factors of change, by identifying the direction and magnitude of change at different times throughout the scenarios' time horizon. To ensure these decisions were well understood by the modeling teams, participants highlighted the logic behind these decisions as well as where there was uncertainty or disagreement amongst the participants.

3.2. Agricultural economic models

All models are simplifications of reality, and full predictability of complex systems like the earth's climate and the global economy

over extended time periods is not feasible (Williamson, 1994; van der Sluijs, 2005; McWilliams, 2007; Knutti, 2008). Quantifying the regional scenarios across a multi-model ensemble allowed for greater exploration of the possibility space around the regional scenarios, by highlighting potential uncertainties where the models disagree (van der Sluijs, 2015; Trutnevyte et al., 2016), and providing a metric of robustness when in agreement. Nevertheless, agreement across an ensemble of models will not ensure the results are accurate (Parker, 2011), and model results should still be treated as conditional projections as opposed to predictions, and serve to spur thought about the future.

Balancing the benefits and costs of quantifying scenarios across a multi-model ensemble is critical when the goal is to help inform decision-making. For this exercise, two economic models that had participated in the Agricultural Model Intercomparison and Improvement Project (AgMIP) were selected (Nelson et al., 2013; Robinson et al., 2014). This facilitated issues of harmonizing scenario drivers across the models. The two economic models used were IIASA's Global Biosphere Management Model (GLOBIOM; Havlik et al., 2014) and IFPRI's International Model for Policy analysis of Agricultural Commodities and Trade (IMPACT; Robinson et al., 2015). Both models are global partial economic models focused on the agriculture sector, with significant levels of geographical disaggregation, allowing the regional scenarios to be simulated within a global context. Table 5 summarizes features of these two models.

Both models assume low levels of commodity differentiation and perfect competition. The two models differ in how they link between global and regional agricultural markets. In IMPACT, country markets are linked directly to global markets with price markups that summarize trade policies and transportation costs, with national net-trade without bilateral dimensions. Commodity markets assume perfect price transmissions with prices determined by global supply and demand. GLOBIOM uses a spatial equilibrium approach of regional markets, where bilateral trade between regions is based on the cost competitiveness of homogeneous goods, including transportation costs and trade policies and barriers (Takayama and Judge, 1971; Schneider et al., 2007). This means that in GLOBIOM regional prices are more sensitive to changes in regional production and demand, whereas in IMPACT they are more sensitive to global price shocks due to changes in global production and demand.

The regional implications of climate change for agriculture are highly uncertain, and there are limited metrics to determine the best (most predictive) climate models (Parker, 2011). Therefore,

multiple models should be used to explore this uncertainty. Like the decision to select economic models, selecting climate scenarios must be tempered by time constraints in processing all of the climate data and running them through crop models for use in the economic models. To simplify this selection process, 4 GCMs (General Circulation Models), which were used previously by both economic models and available through the ISI-MIP project (Warszawski et al., 2014; Rosenzweig et al., 2014; Taylor et al., 2012), were selected. Multiple RCPs (representative concentration pathways) can be used to explore the uncertainty of increasing CO₂ in the atmosphere and its radiative forcing on the environment within each GCM. However, with the projection period ending in 2050 the difference across the RCPs is less notable than through their extended projection to 2100 (Fig. 1). As the objective of the scenario process is to explore a large possibility space, it was decided to use the most extreme climate scenario RCP 8.5 and a constant 2000 climate (similar to RCP 2.6) to provide an envelope of possible climate change effects within the climate scenarios available from the IPCC's 5th Assessment Report.

In addition to the choice in GCMs and RCPs, the choice of crop model is important. Differences between crop models results can be larger than those coming from the economic models alone, as was found by Nelson and Shively (2013). With such uncertainty, it was decided to use more than one crop model in this exercise. To explore this uncertainty each economic model used climate inputs from different crop models. GLOBIOM used EPIC (Environmental Policy Integrated Climate), originally developed by USDA (Williams and Singh, 1995). IMPACT used DSSAT (Decision Support System for Agrotechnology Transfer), developed by the University of Florida (Hoogenboom et al., 2012; Jones et al., 2003). To further expand the possibility space around climate change uncertainty, it was decided to run climate scenarios in DSSAT with 2000 levels of CO₂ fertilization, while EPIC simulated 2050 climate with additional CO₂ fertilization. Table 6 summarizes the global climate scenarios that were eventually combined with the regional scenarios in Table 4.

It should be noted that in both models the final projected yields include economic feedbacks in addition to the biophysical effects modeled by the crop models. These economic effects simulate producers' response to changes in productivity and commodity markets, and include changes in crop allocation, and application of inputs (e.g. fertilizers) in response to changes in relative crop suitability and prices (Leclère et al., 2014; Robinson et al., 2015).

Table 5
Comparing GLOBIOM and IMPACT.

	GLOBIOM	IMPACT
Economic Sector	Agriculture sector including crops, livestock, bioenergy, and forestry	Agriculture sector including crops, agricultural processing, and livestock
Time Horizon	2000–2050/100	2005–2050
Role of Markets	Regional markets linked through global markets determine supply and demand	Global markets determine supply and demand
Geography	Global representing 30 country/regions	Global representing 159 country/regions
Resolution of Production side	Bottom-up approach at detailed grid-cell level (>10,000 worldwide) (4 crop production systems and 8 livestock production systems)	320 food production units (intersection of national and hydrological boundaries) (2 crop production systems and 8 livestock production systems)
Commodities	30 agricultural commodities (18 crops, 5 forest products, 7 livestock products, 9 bioenergy products)	62 agricultural commodities (39 crops, 6 livestock, 17 processed goods)
Environment	GHG accounting, irrigation water use, and endogenous land-use change	Hydrology, water basin management of irrigation water, exogenous and endogenous land-use change
Climate Change	Represented by EPIC crop models	Represented by DSSAT crop models and linked hydrology models

Source: GLOBIOM Havlik et al. (2014); IMPACT Robinson et al. (2015).

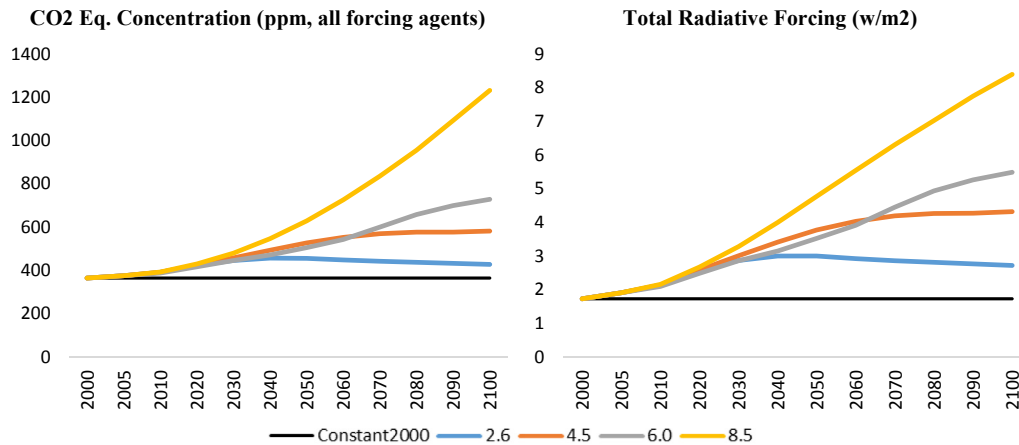


Fig. 1. Comparing representative concentration pathways.

Source: Downloaded from the RCP Database version 2.0.5 (IIASA, 2015); RCP 2.6: van Vuuren et al., 2006; van Vuuren et al., 2007; RCP 4.5: Clark et al., 2007; Smith and Wigley 2006; Wise et al., 2009; RCP 6.0: Fujino et al., 2006; Hijioka et al., 2008; RCP 8.5: Riahi and Nakicenovic, 2007.

Table 6
Climate scenarios.

Representative concentration pathway	General circulation models	Crop model suite ^a	Crops ^b	CO2 fertilization
8.5	GFDL-ESM2M HadGEM2-ES IPSL-CM5 MIROC-ESM	EPIC DSSAT	Barley, Dry Beans, Cassava, Chickpea, Maize, Cotton, Groundnut, Millet, Potato, Rapeseed, Rice, Soybeans, Sorghum, Sugarcane, Sunflower, Sweet Potato, and Wheat Groundnut, Maize, Potato, Rice, Sorghum, Soybean, and Wheat	Additional CO2 fertilization CO2 fertilization at current levels
Constant 2000 climate	Represented by each models baseline assumptions without climate change			

Notes: All GCM climate data comes from CMIP and ISI MIP (Warzawski et al., 2014; Rosenzweig et al., 2014; Taylor et al., 2012) and are downscaled for use in the crop models.

^a The EPIC crop models are used by GLOBIOM, and the DSSAT crop models are used by IMPACT.

^b Crops represented in the economic models not covered by their respective crop model suite are mapped from the above crops based on biophysical similarities.

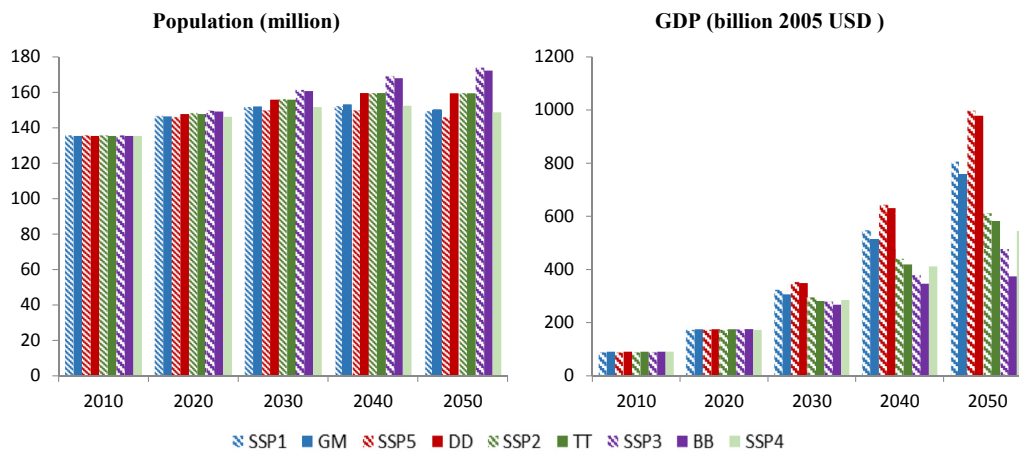


Fig. 2. Southeast Asia Population and GDP compared across the SSPs and Regional Scenarios. Notes: The regional scenarios are clustered and colored according to which of the SSPs the regional scenario is most similar to. The regional scenarios are the Land of the Golden Mekong (GM), The Doreki Dragon (DD), Tigers on a Train (TT), and Buffalo, Buffalo (BB). Source: SSP population (Kc and Lutz, 2014; Jiang and O'Neill, 2015) and GDP (Dellink et al., 2015) downloaded from SSP database (IIASA, 2013).

3.3. Model inputs for each regional scenario

The regional scenarios were quantified following the consistency paradigm (Carlsen et al., 2013), where the SSPs (Moss et al., 2010; Nakicenovic et al., 2014; O'Neill et al., 2014; O'Neill et al., 2015) served as boundary conditions (Wilbanks and Ebi, 2014). This consistency is critical, as the regional workshops only provided semi-quantification for the region, and it was necessary for the two

global economic models to have key drivers for the whole world. The regional scenarios provided different assumptions for gross domestic product (GDP), population, and production costs for farmers. Fig. 2 gives an example of how the GDP and population trajectories of the regional scenarios compare to the regional values in the SSPs (Dellink et al., 2015; Kc and Lutz, 2014; Jiang and O'Neill, 2015).

The SSPs and regional scenarios contain similar narrative

elements (Table 4), which were used to ensure their compatibility with the regional scenarios (O'Neill et al., 2015). For example, SSP1 (*sustainability*) is a future with increased regional coordination, rapid technological growth that allows for improved efforts on both mitigation and adaptation to climate change. The *Golden Mekong* (GM) scenario is an optimistic scenario where the region develops in a sustainable and coordinated way similar to SSP1. The population and GDP growth assumptions are similar, with population growing to around 150 million and GDP to over 750 billion USD by 2050 – though this growth hides inequalities and tensions around migration in GM not featured in the SSP1 narrative. SSP2 is a middle of the road scenario, which is most similar to the *Tigers on the Train* (TT) scenario – although there are differences due to TT's narrative, which focuses on a transition away from agriculture, combined with problems of protectionism. SSP3 is a more negative scenario with slower economic growth and fast global population growth, characterized by greater levels of conflict and fragmentation that stunts efforts to act collectively on climate change issues. This “fragmentation” scenario is most similar to the *Buffalo, Buffalo* (BB) scenario, where there is rapid population growth reaching over 170 million with a stagnant regional economy below 400 billion USD by 2050. SSP5 (*conventional development*) is a scenario of rapid but unsustainable economic growth, which is most similar to the *Doreki Dragon* (DD) scenario. SSP4 a scenario that is represented by higher levels of inequality and the global scenario is not linked directly to any of the regional scenarios, however, it served as a useful guideline for all four regional scenarios which incorporate issues of inequality into their respective narratives. For this exercise, the quantification of the drivers for SSP2 were selected for the rest of the world. This scenario provides a middle of the road future, which allowed us to focus on the implications of the regional scenarios within the region rather than the effects of alternative global trends on development within the region. Nevertheless, in the future it may be of interest to combine the regional scenario with different global scenarios, and allow decision-makers to consider the implications of a changing world on the regional context (for more on the effects of SSPs on global agricultural production, demand, and trade as well as food security see Wiebe et al., 2015 and Hasegawa et al., 2015).

The interaction between population and GDP (per capita GDP, Fig. 3) are critical for both economic models, serving as a proxy for average income, an important determinant of demand. All things equal, a scenario with high income levels will generally see higher levels of total demand, although per capita demand may begin to level off or even decrease for certain commodities as tastes and preferences change with increased affluence (Haley, 2001; Pingali, 2004; Valin et al., 2014).

In general, the GDP per capita story follows the general trends described above, with the GM scenario similar to SSP1, BB to SSP3, DD between SSP5 and SSP1 (due to more optimistic population growth assumptions than SSP5), and TT similar to SSP2 and SSP4. The range of per capita GDP across these scenarios is significant. The more pessimistic BB scenario has a per capita GDP of just over \$2000 by 2050 as compared to over \$5000 and \$6000 for the GM and DD scenarios, respectively. These differing economic growth assumptions have significant effects on demand, which will be seen in the following section.

Each of the regional scenarios has specific assumptions on the development of the agricultural sector in the region. These assumptions were developed at an aggregate commodity level, although different trends were specified by production systems (i.e. cash crops, high vs. low input, etc.). These aggregate trends were then fit around the baseline productivity trends of the two economic models, and were represented as percent deviations from each model's baseline. The original quantification focused on GLOBIOM's modeled commodities, with a mapping to IMPACT commodities based on economic and biophysical similarities (i.e. yams were given the same trend as sweet potatoes, and coffee from other high value cash crops). Fig. 4 summarizes agriculture productivity changes for each scenario, as well as its potential effects on the domestic supply (excluding imports) of calories.

Fig. 4 shows agricultural productivity is closely tied to assumptions on general economic development in the regional scenarios. The GM and DD scenarios, which were more optimistic with respect to per capita GDP growth (see Fig. 3), and increasing technological development show the highest levels of productivity increase (kilocalories/ha), with an assumed increase of calorie supply of nearly 40 percent over the projection period, compared to the more negative 20 to 30 percent assumed under the BB and TT scenarios. Fig. 4 also suggests that agricultural productivity will be increasing over time across the four regional scenarios. However, when we consider the varying assumptions on population growth we see significant differences with respect to the per capita domestic supply of calories, prior to any optimization inside the two models (including imports). If we examine the exogenous assumptions of population growth and the exogenous productivity developments together we see that in BB and TT, for example, the scenarios are similar in terms of productivity, but once population is considered they present different food security stories. High population growth combined with low agricultural productivity in BB, suggests a future where the region will become more dependent on imported food to maintain consumption levels, a troubling outcome in a future with stagnant income growth.

Another critical driver of change in these scenarios is land-use

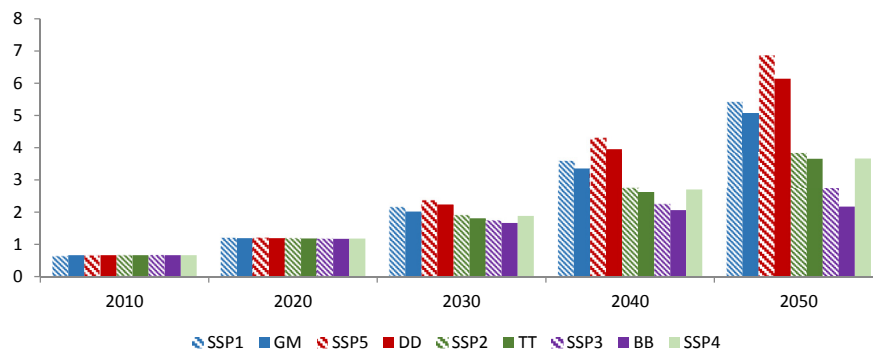


Fig. 3. GDP per Capita (000 real 2005 USD) for Southeast Asia. Notes: The regional scenarios are clustered and colored according to which of the SSPs the regional scenario is most similar to. The regional scenarios are the Land of the Golden Mekong (GM), The Doreki Dragon (DD), Tigers on a Train (TT), and Buffalo, Buffalo (BB).

Source: Computed from population and GDP assumptions

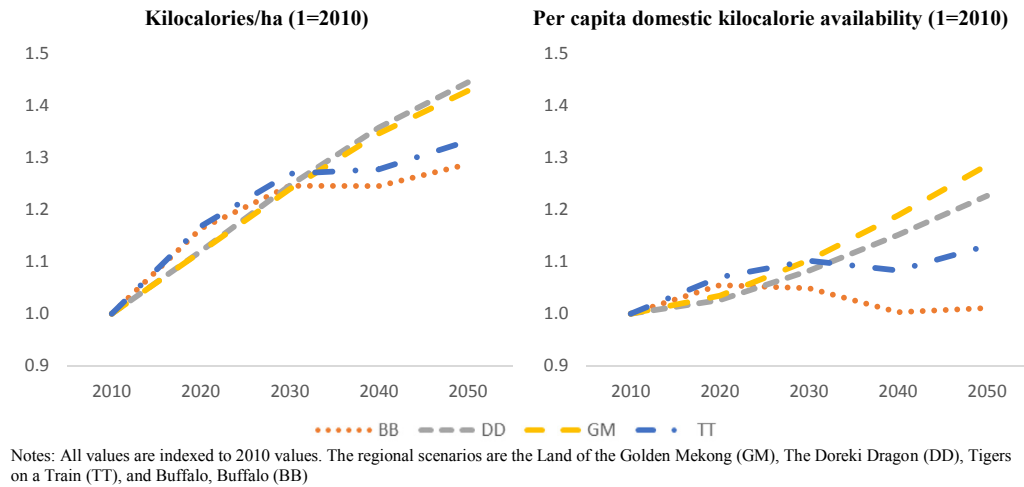


Fig. 4. Total crop productivity across regional scenarios and implication on domestic food supply. Notes: All values are indexed to 2010 values. The regional scenarios are the Land of the Golden Mekong (GM), The Doreki Dragon (DD), Tigers on a Train (TT), and Buffalo, Buffalo (BB).

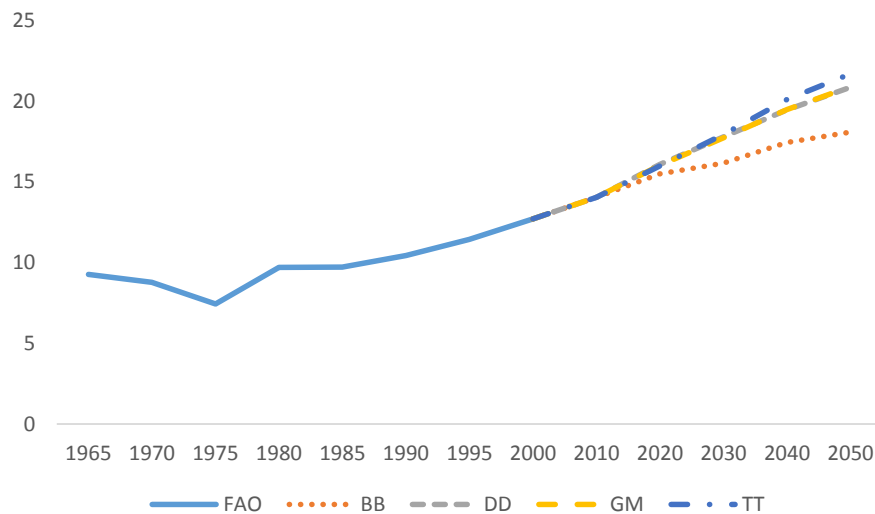


Fig. 5. GLOBIOM cropland projections for Southeast Asia used by both models (million ha). Notes: FAO data represents historical trends on land-used for agricultural purposes. The regional scenarios are the Land of the Golden Mekong (GM), The Doreki Dragon (DD), Tigers on a Train (TT), and Buffalo, Buffalo (BB). Source: FAO (2015) for historical trends. Future land-use projections from GLOBIOM.

change. Pressures to produce greater amounts of food can be met through a combination of both extensive and intensive strategies (Byerlee et al., 2014). Land-use change was explicitly incorporated in the scenario narratives and semi-quantification, as a primary factor of change. To ensure both models represented this factor similarly it was decided to harmonize on GLOBIOM's land-use trends. GLOBIOM was chosen because it considers the major uses of land (e.g. cropland, pasture, forest, etc.), and can simulate the transition between these land-uses. Nevertheless, from previous modeling exercises we recognize that land-use itself is a major point of model uncertainty (von Lampe et al., 2014), and in subsequent workshops the scenarios were extended to include LANDSHIFT to explore alternative futures of land-use change. Fig. 5 summarizes the cropland-use assumptions used for the regional scenarios, and Fig. 6 presents the change in the share of the regional area in terms of the other major land-use categories.

Cropland in the region has been increasing since the 1980s, and faced with increasing global commodity demand is projected to increase in all four of the regional scenarios (Fig. 5). Grassland,

critical to livestock production is also projected to increase in all of the scenarios (Fig. 6). For all of the scenarios, the increased agricultural land (cropland and grassland) comes primarily from unmanaged forest and other natural land. While agricultural land-use is increasing in all of the scenarios, the magnitude of this increase varies.

The DD and GM scenarios see the largest increase in agricultural land, with an increase of 14.5 and 13.3 million hectares respectively. Both scenarios have high productivity assumptions, which increases the value of cropland, with both scenarios showing similar levels of cropland growth (49 percent by 2050). Greater income growth in the DD scenario increases regional demand for livestock products, which drives up the value of grasslands, and explains the additional 1.2 million hectares of grasslands in 2050 as compared to the GM scenario.

In both the TT and BB scenario, slower income growth shifts consumption away from more expensive livestock products to staple crops. Lower demand for livestock products combined with lower productivity growth reduces the demand for additional

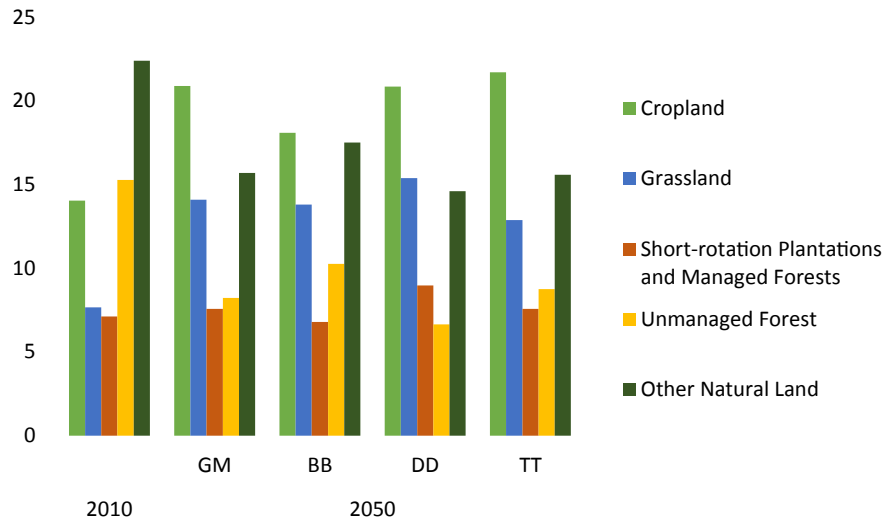


Fig. 6. GLOBIOM projections of land-use change (million ha) by scenario. Notes: Figure shows land-use in Southeast Asia in 2010 and 2050 under the 4 regional scenarios: the Land of the Golden Mekong (GM), The Doreki Dragon (DD), Tigers on a Train (TT), and Buffalo, Buffalo (BB).

Source: GLOBIOM

grasslands in both of these scenarios. In the TT scenario, the region is still competitive in agricultural export markets despite slower productivity growth than in the DD and GM scenarios. To maintain production to meet domestic and export demands extensification is required, which drives demand for cropland area in 2050 to 21.7 million hectares (0.8 million hectares greater than DD). In the case of the BB scenario, the even lower productivity assumptions reduces regional agricultural competitiveness, which drives down demand for additional cropland (more than 2 million hectares less cropland in 2050 compared to the other 3 regional scenarios), as it becomes relatively cheaper to produce agricultural commodities in other regions.

3.4. Model outputs

As the regional scenarios were fit around each model's global SSP2 baseline scenario, it is necessary to recognize the global context these baselines provide. This is true because the region is

relatively small in terms of its share of global agricultural production and demand, with the exception of coffee, where Viet Nam is the world's second largest producer (FAO, 2015), and rice, where Southeast Asia accounts for 25 percent of global production (Baldwin et al., 2012). Thus, we will present each model's baseline alongside the model results for the regional scenarios.

In general, GLOBIOM shows larger increases in production over time than IMPACT in its baseline, as well as for all the regional scenarios. Nevertheless, in both models we observe increasing agricultural production across all of the scenarios. There is a clear outlier in the magnitude of this increase, as both models show lower growth in production in the BB scenario. This slower growth in agricultural production can be attributed not only to the lower assumptions on productivity growth (Fig. 4), but also on the smaller increase in cropland (Fig. 5). Among the remaining three regional scenarios, we see different pathways in achieving similar levels of total agricultural production in 2050. The TT scenario relies more on agricultural extensification, whereas higher productivity leads

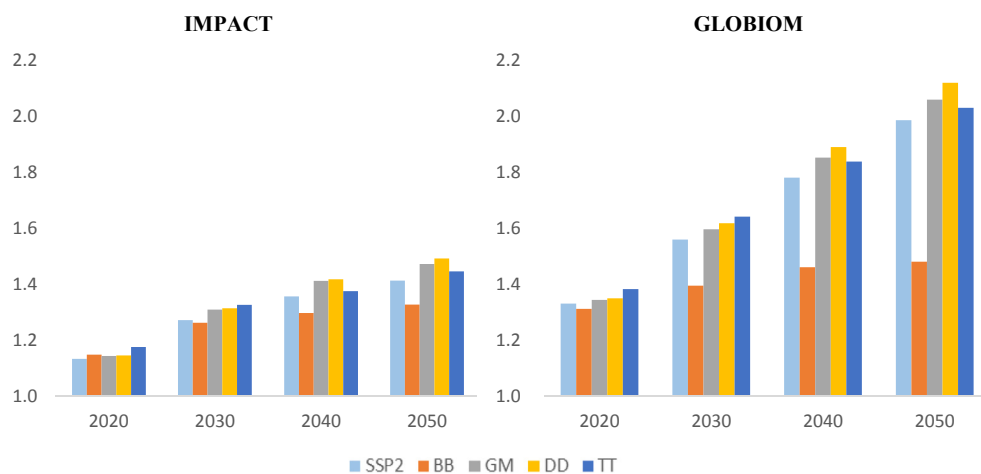


Fig. 7. Total crop production (metric tons, indexed to 2010) across the scenarios. Notes: Values are indexed to 2010. SSP2 shows the baseline scenario results for each model along with the 4 regional scenarios: the Land of the Golden Mekong (GM), The Doreki Dragon (DD), Tigers on a Train (TT), and Buffalo, Buffalo (BB).

Fig. 7. Total crop production (metric tons, indexed to 2010) across the scenarios. Notes: Values are indexed to 2010. SSP2 shows the baseline scenario results for each model along with the 4 regional scenarios: the Land of the Golden Mekong (GM), The Doreki Dragon (DD), Tigers on a Train (TT), and Buffalo, Buffalo (BB).

the way under the DD and GM scenarios. Fig. 7 summarizes the consequences of the different productivity and land assumptions for the crop sector as a whole. There can be significant differences by crop, which we will illustrate by comparing model results for rice, which was treated as a commercial crop by stakeholders, and sweet potatoes, which was treated as a staple crop.

3.4.1. Comparing rice and sweet potato yields

The baseline assumption (SSP2) for rice productivity across the two models is rather low with stagnant yield increases in IMPACT of under 10 percent by 2050 compared to over 20 percent in GLOBIOM, which reflects slow rice yield growth since the Green Revolution (Baldwin et al., 2012), and significant additional investments in agricultural research and extension needed to rapidly close the regional rice yield gap (Laborte et al., 2012; Fischer et al., 2014). The sweet potato baselines differ more across the economic models, with IMPACT showing yield growth of over 50 percent by 2050, more than double the yield growth assumed by GLOBIOM. This model uncertainty reflects significant yield fluctuations in the 1990s and 2000s (FAO, 2015).

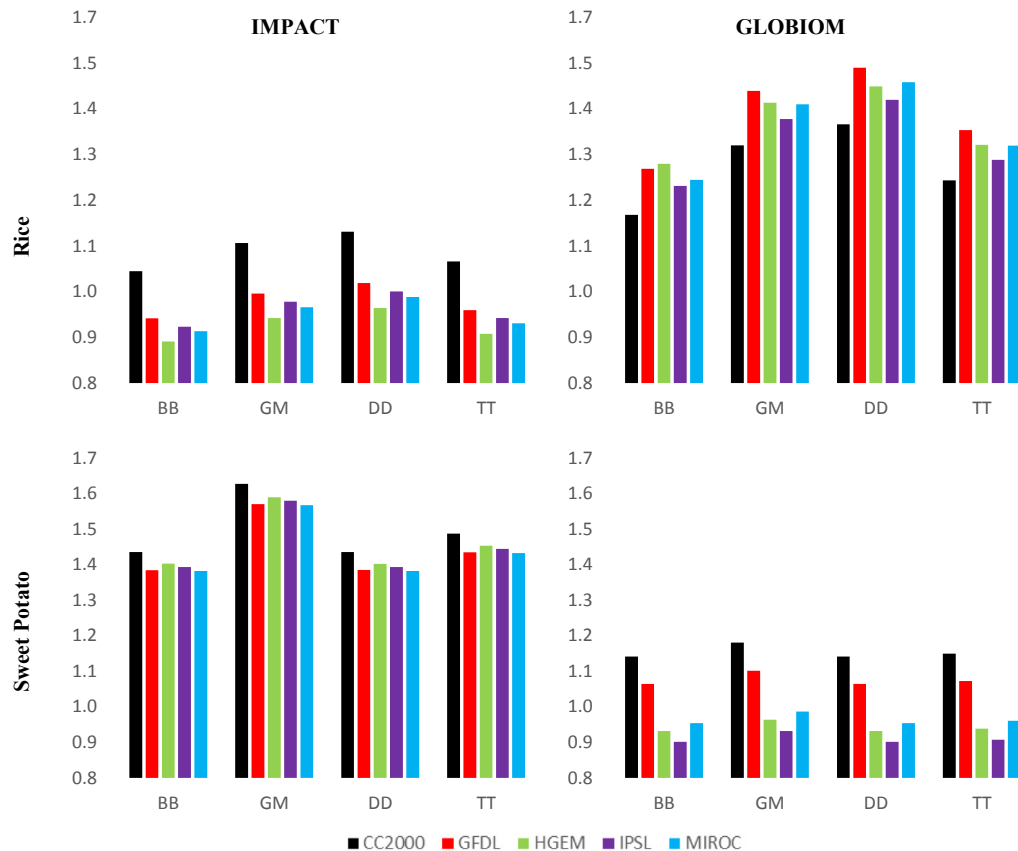
Southeast Asia is a major rice exporter (Baldwin et al., 2012; FAO, 2015; Fischer et al., 2014), and as such it is more closely tied to global markets, leading to similar rice results in both economic models. Through 2030, rice yields increase across all of the scenarios. However, after 2030 rice yields diverge, with continued growth occurring under the DD and GM scenarios (increasing between 3–5% and 3–8% over the baseline for IMPACT and GLOBIOM respectively). The TT scenario sees a plateauing with final yields at similar levels as the baseline SSP2 scenario (1 percent and 2 percent lower yields compared to SSP2 for IMPACT and GLOBIOM respectively). The BB scenario is the most negative scenario with yield

declines of 3 and 9 percent from the SSP2 baseline for IMPACT and GLOBIOM respectively. Sweet potatoes serve as a staple and emergency food crop in Southeast Asia (Campilan, 2009), and were therefore given a different treatment in the scenario semi-quantification. In contrast to rice, where the highest yields are in the DD scenario, the highest sweet potato yields are in the GM scenario, which sees yields in 2050 about 13 percent higher than in the DD scenario. This difference is due to the role of agricultural industrialization in the DD scenario, which presents greater difficulties to small shareholder farmers, the primary producer of sweet potatoes. Fig. 8 summarizes the differing yield trends for IMPACT and GLOBIOM for both crops.

Model uncertainty is also evident in the effects of climate change, which are summarized in Fig. 9. In contrast to the baseline rice assumptions, the two models disagree on the potential effects of climate change on rice. In IMPACT, climate change has a negative effect, with 10 percent yield declines in 2050 compared to the constant 2000 climate scenario (CC2000). In GLOBIOM, climate change has a positive effect with yield increasing by about 10 percent. To put into context, this yield effect is similar in scale to the changes in yields observed in the DD scenario compared to the SSP2 scenario (Fig. 8). This suggests the role of CO₂ fertilization is a point of major uncertainty in the impact of climate change on rice yields. For sweet potatoes, both models agree climate change is likely to have a negative effect. However, the models differ on the magnitude of the losses with yields declining by less than 5 percent in IMPACT compared to an average decline of 15 percent in GLOBIOM. This larger negative shock combined with low yield growth assumptions has GLOBIOM projecting 2050 sweet potato yields below 2010 levels in 3 of the 4 GCMs used. Such a negative shock would have a profound effect on sweet potato production in the



Fig. 8. Comparing rice and sweet potato yields under a constant 2000 climate (indexed to 2010). Notes: Values are indexed to 2010. SSP2 shows the baseline scenario results for each model along with the 4 regional scenarios: the Land of the Golden Mekong (GM), The Doreki Dragon (DD), Tigers on a Train (TT), and Buffalo, Buffalo (BB)

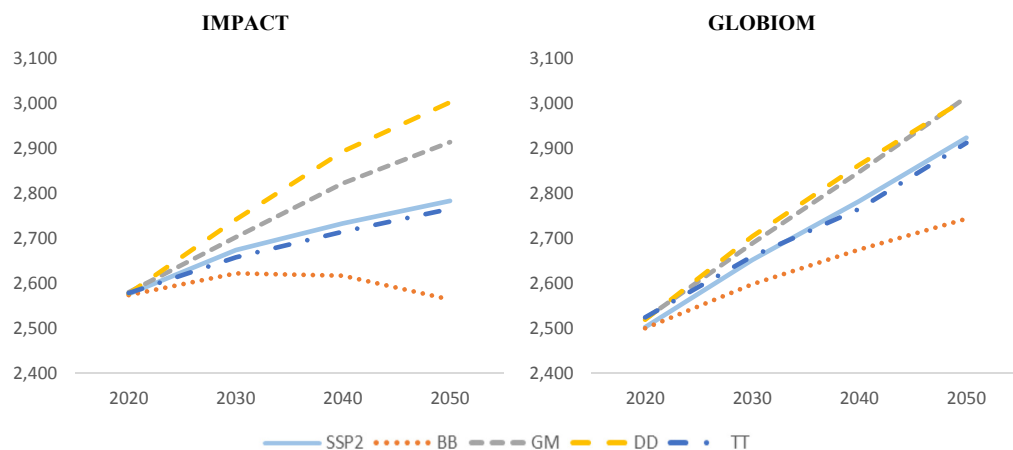


Notes: Shows yields in 2050 indexed to 2010 across the four regional scenarios and four GCM climate scenarios represented by DSSAT with no additional CO₂ fertilization in IMPACT, and by EPIC with additional CO₂ fertilization in GLOBIOM. The four regional scenarios are the Land of the Golden Mekong (GM), The Doreki Dragon (DD), Tigers on a Train (TT), and Buffalo, Buffalo (BB).

Fig. 9. Comparing rice yields in 2050 with and without climate change (indexed to 2010). Notes: Shows yields in 2050 indexed to 2010 across the four regional scenarios and four GCM climate scenarios represented by DSSAT with no additional CO₂ fertilization in IMPACT, and by EPIC with additional CO₂ fertilization in GLOBIOM. The four regional scenarios are the Land of the Golden Mekong (GM), The Doreki Dragon (DD), Tigers on a Train (TT), and Buffalo, Buffalo (BB). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

region, with potentially large effects on temporal food security. These negative effects could offset some of the gains expected from broad regional development even in the more optimistic scenarios. The agreement across both models on the negative effects of

climate change suggests policy-makers may want to consider targeted investments to help mitigate the effects of climate change on sweet potato farmers, either by improving varieties and management practices, or assisting them in moving to alternative crops



Notes: Values are indexed to 2010. SSP2 shows the baseline scenario results for each model along with the 4 regional scenarios: the Land of the Golden Mekong (GM), The Doreki Dragon (DD), Tigers on a Train (TT), and Buffalo, Buffalo (BB).

Fig. 10. Regional Kilocalorie Availability (kcal per capita per day). Notes: Values are indexed to 2010. SSP2 shows the baseline scenario results for each model along with the 4 regional scenarios: the Land of the Golden Mekong (GM), The Doreki Dragon (DD), Tigers on a Train (TT), and Buffalo, Buffalo (BB).

better suited for future climates.

3.4.2. Food security implications

Income is the biggest driver of changes in food demand and Fig. 10 illustrates this with the highest increase in kilocalorie availability by 2050 in the GM and DD scenarios. The TT scenario is similar to the baseline SSP2 scenario with respect to its per capita GDP trend, and the food availability in the region under this scenario is similar to the global SSP2 scenario, with steady improvement to around 2800 kcal/person/day in IMPACT and 2900 kcal/person/day in GLOBIOM. The BB scenario, presents decision-makers with a challenging future with respect to regional food security. IMPACT suggests no gains in calorie availability in 2050 from 2010, with calorie availability under 2600 kcal/person/day. GLOBIOM projects some growth in calorie availability, but it is slower than under its baseline (8 percent less in 2050). It should be noted that while average calorie availability across the other three scenarios is increasing, the region could face issues with respect to economic access to food, as all the scenarios contain narrative elements involving inequality. Currently, both models simulate demand on a single representative consumer per country and cannot simulate the effects of income inequality and economic access to food. Future modeling efforts will be needed to explore this topic.

4. Using scenarios to inform decision-making in Southeast Asia

The regional scenarios were designed to provide a broad platform to inform diverse policies at various scales (e.g. regional, national, and sub-national). To date, the scenarios have been used in the region in several policy-making processes, showing the adaptability and reusability of these scenarios, a strength of this scenario approach.

The scenarios were first used to inform regional policies in Cambodia. Upon the conclusion of the first workshop in Viet Nam, the Cambodian Ministry of Agriculture, Forestry, and Fisheries (MAFF) expressed interest in embedding the scenarios in the development of their Climate Change Priorities Action Plan (CCPAP). This was done to set policy priorities to better target the CCPAP's projected 164 million USD budget, and build institutional capacity to use scenarios. Over the course of 6–8 month and in collaboration with one of this paper's authors, the scenarios were used in workshops with donors and implementing partners to help develop the CCPAP. The scenarios stimulated discussions around the challenges presented by climate change and economic development. They highlighted the need for more holistic national policies to achieve climate-smart food systems, an overall objective of the CCPAP. This conclusion led to the inclusion of additional scenario work as a cross-cutting activity in the finalized CCPAP (Vervoort and Peou, 2014).

As this work moved forward in Cambodia, parallel efforts went ahead in Viet Nam. In collaboration with the United Nation's Food and Agriculture Organization (FAO), a workshop was held in Viet Nam in May 2014, with stakeholders from government agencies, research institutions like the Northern Mountainous Agriculture and Forestry Science Institute, the private sector, and civil society. The objective of the workshop was to use the regional scenarios to help review and revise climate-smart agriculture investments for Northern Vietnam (FAO/CCAFS, 2014). The stakeholders considered the potential efficacy of the different investment proposals under alternative futures. They explored the potential challenges and complex interactions between the many dimensions of the scenarios. The insights gained from this thought exercise were then integrated into improved versions of the proposals, which have since been taken into further stages of development.

In a third policy engagement process, a regional workshop, organized by CCAFS and UNEP WCMC, extended the scenarios to evaluate and improve national policies in Cambodia, Laos, and Viet Nam. In this workshop, which brought together a new group of national stakeholders, there were parallel objectives to review policies for each country using the regional scenarios. For the Cambodian stakeholders the objective was to review the finalized CCPAP, and devise a plan for its implementation. For the Laotian stakeholders the objective was to evaluate the strengths and weaknesses in their government's economic development plan. For the Vietnamese stakeholders the objective was to review their government's agriculture development policy and develop plans for its implementation. At the forefront of these policy discussions were environmental tradeoffs with respect to agricultural and economic objectives. To better reflect these potential tradeoffs the scenario quantification and analysis was extended to include LANDSHIFT (see Appendix A for more information, Schaldach et al., 2011). LANDSHIFT is a spatially explicit land-use model that operates at a higher resolution than GLOBIOM and IMPACT, and was used to spatially project land-use and land-cover changes due to IMPACT's own cropland assumptions. This also allowed for estimation of changes to biodiversity and ecosystem services (van Soesbergen and Arnell, 2015), supplementing GLOBIOM's land-use results, and to explore the uncertainty around land-use change assumptions. The scenario discussions in this workshop, similar to other regional experiences engaging with the scenarios, left stakeholders with a greater appreciation and awareness of uncertainty and the need to embed more holistic approaches to policy-making and planning. In the words of one of the stakeholders, “the scenarios make us look at other aspects and elements” in forming policies that are “more realistic and inclusive” (van de Grift and Vervoort, 2015).

In this third policy engagement, a survey was done to identify the stakeholder's policy priorities. 67 priorities were identified by the stakeholders, of which 52 could be addressed through the full set of scenario outputs (see Appendix B for the full list of priorities and scenario coverage). The models individually could address between 20 and 40 percent of the policy priorities. There was significant overlap across the models by design, nevertheless, when combined they could address more than 43 percent of the policy priorities. The scenario development process was designed to allow for further extension of the scenarios as needed, and the range of coverage (75 percent of priorities) from the full semi-quantified factor set should allow for straightforward extension of the scenarios to more models. This feature of the development process was put to effect with the extension of the scenarios using LANDSHIFT. The breadth of coverage of the regional scenarios would have been difficult to achieve under a more traditional scenario set that incorporated fewer factors of change and only one model. The stakeholders themselves identified the value of this multidimensional approach, and declared the resulting scenarios superior to previous scenarios created in the region, which were less broad and inclusive. The fact these scenarios have resonated with regional stakeholders, over time, and across many different uses, suggests these scenarios will remain relevant into the future.

5. Discussion and conclusions

The successful application of the regional scenarios to different policy engagement processes argues for the value of a multi-factor, multi-state, multi-model approach to scenario development. The larger policy guidance process must generally allow for a reinvention and reinterpretation of the scenarios, based on the needs and scope of any specific process, ensuring a good fit between the scenarios and the plans they are informing (Vervoort et al., 2014).

Developing and quantifying scenarios in models can take significant time, which can make customizing model representation for every policy question costly. If, however, the scenarios are designed in a broad and multi-dimensional fashion as they were in Southeast Asia, they can be relevant for a range of policy uses, only needing minor elaboration and reinterpretation.

The approach used in this study presents a powerful methodology that allows for a systematic way of organizing and relating factors and factor-states in developing diverse multi-dimensional scenarios. It facilitated consensus building in the scenario development process, by incorporating additional elements through the use of sub-factors of change. It also spurred a conversation with decision-makers' around their power to affect change versus responding to it, by incorporating contextual and strategic elements in the scenarios. Consequently, this approach allowed for more aspects to be analyzed than would be possible under a traditional two-axes approach, which has allowed the scenarios to be applicable to a wide array of policy questions, many of which have arisen after the scenarios have been quantified. The large overlap between the subsequent policy engagements and the original scenario scope has shown them to be adaptable to the needs of a wider public than the original workshop participants in Ha Long.

Models are essential for quantitative interpretation of complex scenarios. However, the use of any particular model can greatly simplify the rich narrative of a scenario. Using models can threaten to confuse the purpose of the scenario development process, from developing rich and plausible futures to parameterizing a model, which would be a sub-optimal use of all of stakeholder expertise (Petersen et al., 2011). Nevertheless, the quantitative model outputs can complement the knowledge gained from qualitative discursive analyses, illustrating magnitudes of change as well as connecting a broad array of stressors simultaneously and consistently to assess their cumulative effects and expose important interactions and tradeoffs. Tensions between the two forms of representation can highlight and allow the exploration of different worldviews (e.g. participants were encouraged to question land-use-change maps based on their understanding of the multi-dimensional qualitative narratives). This can help decision-makers to develop a deeper understanding of the uncertainties they face (Trutnevytem et al., 2016).

Quantifying scenarios with a multi-model ensemble as was done in this exercise has many advantages. It encourages participants to consider a broader range of possibilities, and allows for more scenario richness to be captured, which stakeholders identified as a strength of this approach. Nevertheless, making sure multiple models consistently represent the scenarios is time intensive, and requires extensive collaboration across modeling groups. This collaboration in scenario quantification can be facilitated by having the modelers present at the scenario conception, which embeds knowledge of the background discussions that led to the scenario creation in the modeling efforts. This participation carries the risk of distracting stakeholders from scenario building, but when managed properly provides opportunities to explain the models' strengths and weaknesses, which helps manage future expectations.

The costs of adding additional models can be significant. Harmonizing scenario inputs is not straightforward even among similar models, and additional models must be explained to decision-makers to ensure they understand the uncertainty each model highlights. Nevertheless, using multiple models with different assumptions and areas of focus means a broader range of scenario results can emerge that may be suitable to more policy uses. For instance, the IMPACT model's country-level results were useful for the (sub-) national investment plans in Viet Nam, and

were more compatible with LANDSHIFT; GLOBIOM's stronger spatial focus and information on multiple sectors for land-use supported priority setting in Cambodia's CCPAP. As such, we believe the benefits outweigh the costs, and a multi-model ensemble can broaden the possibility space, while highlighting points of greater uncertainty, facilitating a conversation around the scenarios and their implications.

The evaluation of potential environmental impacts of socio-economic development globally and regionally are often expressed as simple growth rates (or rates of loss) based on changes across a few factors or drivers, such as agricultural expansion, or population growth. The multi-factor, multi-state and multi-model approach presented here allows for the exploration of complex tradeoffs between agriculture and the environment under a range of socio-economic and climatic change assumptions that would be more constrained under more traditional scenario processes. The exploration of these tradeoffs and potential unintended consequences is critical to improving decision-making related to food security and climate change.

Despite our efforts, many elements of the stakeholder-generated qualitative scenarios were not captured by the models, or have been represented in a simplified way (e.g. story elements around governance and coordination, transparency and corruption, conflict, community-level resilience, etc.). For this reason, the model results were treated not as the final results of the scenario process, but as part of an overall scenario conversation. In communicating model results, the gaps in the model's scenario representation were explained to help build the capacity of decision-makers to comprehend multi-dimensional uncertainties, the overall objective of this regional scenario process. We believe that approaches similar to the one presented here could contribute to better policy-making by increasing the dimensions of uncertainty included in the scenarios used by policy-makers to systematically test the robustness and efficacy of future policies.

Author contributions

DMD, JV, and AP wrote the paper.

DMD, JV, and AP quantified scenarios for the models.

DMD, AP, SI, and PH analyzed scenario results.

JV and RP coordinated regional engagement.

JV, AP, SI, SL, AH, RP, MS, MV, AvS, AnA, BS, AsA, and LL assisted in scenario development and semi-quantification.

All authors were involved with research design.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <http://dx.doi.org/10.1016/j.envsoft.2016.05.008>.

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